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Modified Atmosphere Packaging for Fresh-Cut Produce

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Modified atmosphere packaging (MAP) is effective in maintaining quality through its effects on modification of the gas composition in the package headspace (Schlimme and Rooney, 1994; Jacxsens et al., 2002; Kim et al., 2003; Luo et al., 2004). The degree of atmospheric modification within a modified atmosphere package is a consequence of the respiratory O_2 uptake and CO_2 evolution of the packaged produce and the rate of gas transfer across the package film (Al-Ati and Hotchkiss, 2002). But several factors impinge on this basic understanding and directly influence the final package atmosphere, including temperature, product weight, and package surface area (Bell, 1996). There have been previous reviews of the effects of modified atmospheres (Mir and Beaudry, 2004; Varoquaux and Ozdemir, 2005) and so the discussion in this chapter will focus on recent findings or those which have not been discussed in detail by other authors.

The intent of this chapter is to provide the reader with a broad appreciation for MAP of fresh-cut processed fruit and vegetable products. To achieve this goal, the discussion will range from packaging design considerations to understanding the effects of modified atmospheres and humidity on the quality and shelf life of the fresh-cut products within the package. Finally, the authors' views on future research and technology needs will be discussed.

18.1 Packaging Technology

18.1.1 Packaging Materials

There is an ever increasing variety of packaging materials available for MAP for fresh-cut produce. The polymers, films, structures, and formats, which make up this type of packaging can include flexible packages, rigid containers, engineered oxygen transmission rate (OTR) polymers, microperforated materials, as well as combinations of all of the above. Within these broad categories, there are also ancillary technologies that have been developed to improve package performance, including easy-peel lid structures, antimicrobial packaging, cook-in packaging, and active and intelligent packaging. Each of these formats has strengths and weaknesses that impact their desirability for a particular fresh-cut produce application. The choice of the correct structure must be determined by matching the strengths of particular structure with the fresh-cut product characteristics (i.e., physiological characteristics), engineering, marketing, and manufacturing requirements of the package, while at the same time minimizing or masking particular weakness.

Specific parameters that have a direct impact on the choice of packaging format include product type, product quantity, market application (food service, retail, or club store), package dimensions, stiffness, graphics, marketing, cost, environmental impact, reusability, easy open feature, cook-in requirement, etc. In order to understand and then effectively match the key parameters to the optimal packaging format, it is essential that communication between grower, processor, and packaging supplier exists. In addition, the MAP design process must be seamlessly incorporated into the overall new product development process.

18.1.1.1 Polymers

There are a variety of polymers used in fresh-cut produce MAP. A portion of these polymers are used in primarily flexible packaging structures, a portion are used in primarily rigid packaging structures, and a portion are used in both types of applications. Each specific polymer has physical, chemical, and gas transmission rate properties that are unique to that polymer. Design of a packaging structure entails matching the specific polymer properties to the requirements of the MAP application. See Table 4.1 for a listing of commonly used polymers and their corresponding attributes. For fresh-cut modified atmosphere applications a polymer's gas transmission rates, specifically, OTR and carbon transmission rate (CO_2TR) are key attributes. The transmission of gases across packaging structures governed by several factors that are related through Fick's law:

$$J_{gas} = \frac{A \times \Delta C_{gas}}{R} \qquad (18.1)$$

where

J_{gas} is the total flux of gas (cm^3/s)
A is the surface area of the film (cm^2)
ΔC_{gas} is the concentration gradient across the film
R is the resistance of the film to gas diffusion (s/cm)

The gas flow across a film increases with increasing surface area and increasing concentration gradient across the film. In contrast, the gas flow across the film decreases with increasing film resistance to gas diffusion. Designing and controlling gas transmission rate is one of the fundamental underlying principles of successful MAP application in commercial practice. Blends, coextrusions, and films comprised of specific polymers combine to create a package with a specific OTR. The optimal OTR selection for a MAP film for a specific fresh-cut product is dependent upon the respiration rate(s) of the produce, product weight, the internal package dimensions, the targeted atmosphere composition, and product handling temperature.

The goal of MAP of fresh produce is to create an equilibrium package modified atmosphere with an O_2 partial pressure low enough and a CO_2 partial pressure high enough to result in beneficial effects to the produce and not be too low or too high, respectively, such that they become injurious (Zagory, 1998). Therefore both O_2 and CO_2 gas transmission selection is necessary to create an optimal modified atmosphere. However, gases diffuse through polymeric films at different rates: carbon dioxide generally diffuses through most polymer films at rate from between two to five times faster than oxygen (Al-Ati and Hotchkiss, 2002). The ratio of CO_2 transmission rate to O_2 transmission rate of a film is termed the beta value of a particular film. Polymeric films therefore generally have beta values ranging from 2 to 5, with an average of 3. The beta value of a modified atmosphere package will have a direct bearing on the final modified atmosphere achieved within the package (Al-Ati and Hotchkiss, 2002). For example, in standard polymer films, it is generally possible to achieve a low O_2 level (e.g., 2 kPa) in combination with a moderate CO_2 level (e.g., 7 kPa).

The respiration of specific fresh-cut produce items is determined through routine testing procedures. A number of universities specialize in product respiration calculations (e.g., University of California, Davis, California). In addition, there are produce respiration testing protocols available through private consultancy companies (e.g., The JSB Group, LLC) and these can be performed in-house at the processing plant. It must be kept in mind that the respiration of a piece produce is temperature dependent (Varoquaux and Ozdemir, 2005). Product temperature is therefore critical in determining the product respiration rate. Since package OTR is respiration rate dependent, then package OTR determination is temperature dependent as well. Therefore if temperature varies throughout the product life cycle the MAP cannot be optimized or relied upon. Temperature is so critical to MAP performance and if temperature variations are too significant it can actually do more harm than good (Tano et al., 1999; Varoquaux and Ozdemir, 2005).

18.1.1.2 High OTR Materials and Technologies

The relatively high respiration rates of many fresh-cut produce items (Gorny, 1997) require that they be packaged in MAP films that have OTRs above 750 cc/100 in.^{2}/atm/day (~12,000 cc/m^2/atm/day). Generally, there are two approaches to achieving the required high OTRs: either high OTR polymers or microperforations can be used. High OTR polymers include ultralinear low-density polyethylene (ULDPE), plastomer metallocenes, and high percent ethylene vinyl acetate (EVA). Refer to Table 4.1 for typical values of specific high OTR polymers. The density and crystallinity of the polymer dictate the

OTR: the lower the density the higher the OTR. However, OTR is not the only important physical parameter that is altered as polymer density changes. Stiffness, clarity, hot tack, and ultimate seal strength are also impacted. As the density decreases, stiffness decreases, hot tack increases, clarity decreases, and ultimate seal strength decreases. Hence, high OTR resins are very tacky and require additional slip and antiblock additives to optimize behavior during manufacture and fresh-cut product processing. The additional additives can also have a significant impact on final OTR, often reducing the OTR to a lower than desirable level. The specific choice of combination and processing protocol of high OTR polymers is dependent on what attributes, in addition to high OTR, are necessary in the finished film. There is also an upper limit to the OTR for these polymers. Currently without any additives, the upper limit to OTR is 1000–1200 cc/100 in.^{2}/mil/atm/day (15,500–18,600 cc/m^2/mil/atm/day). In a slip and antiblock modified format, this upper limit is nearer to 900–1000 cc/100 in.^{2}/mil/atm/day (13,950–15,500 cc/m^2/mil/atm/day). These OTR levels are for the specific polymer alone. Combined with other polymers in either a coextrusion or blend will further reduce the effective OTR. See Chapter 4 for equations used to calculate OTR in both polymer blends and film coextrusions.

18.1.1.3 Microperforated Films

An alternative method for achieving high OTR packaging structures is through the use of microperforation technology (Lougheed, 1992; Aharoni and Richardson, 1997). This technology involves creating, through various means, holes of several micrometers in the packaging structure. The hole size and configuration can vary with the specific perforation technology but microperforations are not visible to the naked eye and can range from 40–200 μm in diameter. In addition, the spatial placement of the holes within the package itself is critical. Ensuring that the holes are not blocked or obstructed in any way is critical to the success and desired control of gas transmission. Microperforated films are similar to high OTR polymers in that there are OTR limitations. However, the limitations are at the lower end of the range and not critical for MAP applications in fresh-cut produce. Typical OTRs for microperforated films begin at 250 cc/100 in.^{2}/mil/atm/day (i.e., 3875 cc/m^2/mil/atm/day) at the lower end. Gas transmission rates of microperforated film are determined by the size of the individual micro holes and their corresponding placement and frequency. The number of microperforations required to be in a package are directly proportional to the desired OTR (i.e., as the OTR requirements increase, so do the number of holes). Since microperforated structures cannot have less than one hole, the gas transmission rate through a single hole dictates the lowest possible transmission rate. It must be cautioned that microperforated MAP with only one hole can be problematic due to the high potential risk of blockage for that single perforation. With two or more holes, the risk of blockage of all holes declines and also there is more uniform gas transmission throughout the package. In order to avoid a package design with only one microperforation, consideration should be given to altering other key OTR control parameters, such as product weight or package dimension.

The diffusion rates of atmospheric gases through microperforations are very similar. In effect, the diffusion rates of CO_2 and O_2 are virtually identical, i.e., the films have a beta value of 1. Therefore, in these films targeted atmospheres with low O_2 partial pressures (e.g., 2 kPa) and high CO_2 partial pressures (e.g., 19 kPa) can be achieved. The beta value difference between polymeric and microperforated structures provide for significantly different ranges in final modified atmosphere composition. This fact needs to be accounted for in the packaging design process.

Macroperforations, which are visible to the naked eye, should not be considered to be equivalent to microperforations. The gas movement through these larger, visible holes utilized in macroperforated films is too great to consistently modify and control the gas composition within a package. Therefore a low O_2 modified atmosphere is not feasible with macroperforated film. This does not mean, however, there is not a need for macroperforated films. Since the gas transmission is so high, a macroperforated structure will virtually never become anaerobic (i.e., O_2 levels falling to 0 kPa) even under temperature abuse situations. If it is a priority to have a fresh-cut produce package designed such that it cannot become anaerobic under any circumstance and exposure atmospheric levels of O_2 do not significantly reduce shelf life of that product, then macroperforation technology may be applicable.

18.1.2 Package Formats

Choosing the correct packaging format is an integral step in modified atmosphere package design. The process of determining the correct packaging format must include input from all stake holders, including the fresh-cut processor, packaging manufacturer, raw material suppliers, and the consumer. In general there are three types of formats that are most commonly used in fresh-cut produce modified atmosphere packaging: flexible packaging, rigid packaging, and active/intelligent packaging. Within each of these broader categories, there are numerous variations and permeations.

18.1.2.1 Flexible Packaging

Flexible packaging is the most common format for fresh-cut produce MAP in North America. Typically this format is available as preformed bags, roll stock, and stand-up pouches. A variety of additional features, such as easy opening and resealability, can be designed into the package. Each format type has its own challenges, strengths, and weaknesses.

Preformed bags are ideal for initial testing and start up operations since order quantities can often be minimized allowing for smaller initial packaging costs. As the name implies preformed bags are preformed with three sides closed and one side remaining open for filling with product. Although not always the case, most preformed bag applications coincide with a hand filling operation in the processing line. Generally, since the final seal on the bags are sealed by hand, it is important that they are sealed consistently ensuring the package dimensions are constant. Failure to situate the seal at a consistent location in a bag will result in variation in internal package surface area and ultimately variation in the total bag OTR. Preformed bags come in a variety of structures and graphics, but are often sold as an off-the-shelf item versus custom designed for each specific application. Ultimately the decision process involves the reconciliation of trade-offs between ideal OTR, off-the-shelf convenience, and cost.

Roll stock is the most common form of modified atmosphere flexible packaging for retail applications. Roll stock packaging configurations can range from the very basic monolayer films to complex reverse printed multilayer laminations. Unlike preformed bags, the packaging structure is not supplied sealed at all but rather delivered cut to the final running width and wound on rolls. In order to obtain the final filled package, the roll stock is run on a form-fill-seal packaging machine. Most common for fresh-cut modified atmosphere packaging applications is the vertical form, fill, and seal (VFFS) machine (Figure 18.1). Form, fill, and seal machines can be configured to run either a lap or a fin-and-crimp seal (see Chapter 4 for a detailed explanation of lap versus fin-and-crimp sealing). No matter what the sealing configuration, the width of the seals cannot be included in the surface area calculations for total package OTR determination. Depending upon the specific machine configuration the seal width can be a significant percentage of

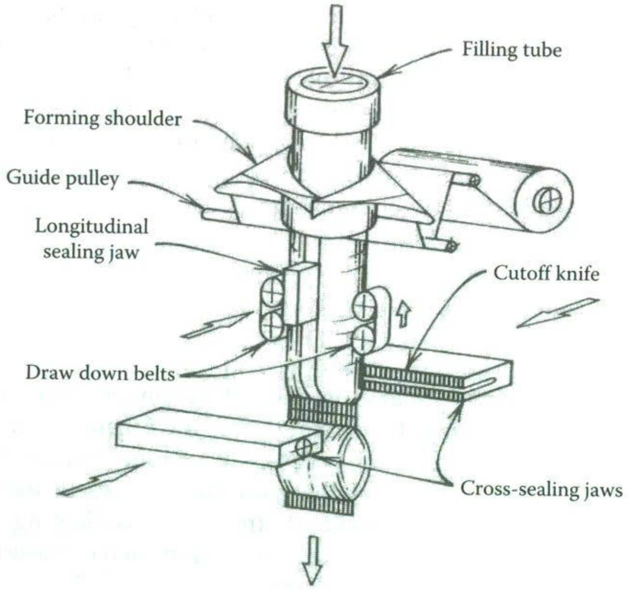

FIGURE 18.1
Schematic representation of a VFFS packaging machine. A precise weight of fresh-cut product is introduced through the filling tube at the top of the drawing. Simultaneously, a bag is being formed around that tube from packaging roll stock which has a width dimension specified for this particular machine. The longitudinal sealing jaw welds the side seam of the newly formed bag. Cross-sealing jaws simultaneously seal the top of the previously filled bag and also the bottom of the currently forming bag in one operation. A cutoff knife is interposed between the two sealing bars of the cross-sealing jaws to separate the two bags as the seals are being formed. Once the bottom seal of the current formed bag is completed, the weighed fresh-cut product is dropped into it and the draw down belts pull the film down one-length of a bag, allowing the top to be sealed with the cross-sealing jaws, while also making the bottom of the next bag. (Brandenburg, unpublished figure.)

the package area. With roll stock structures, which are converted into finished packaging on VFFS machines, there are physical structural properties that become more important compared with preformed bags. These parameters include coefficient of friction (COF), seal initiation temperature, and hot tack seal strength. Although flexible modified atmosphere roll stock packaging is sometimes offered off-the-shelf it is most commonly offered and effective as a customized structure for a specific fresh-cut application to be run of a specific VFFS machine.

Stand-up pouches can be obtained either in a preformed or roll stock format. The distinguishing feature is that at least one side of the bag is gusseted, allowing the pouch to stand on its own. This stand-up feature allows for product differentiation on the store shelf. Stand-up pouches can be designed and manufactured with either solid polymer or microperforated film technology. Due to the stand-up feature, effective package surface area is increased, which allows for a lower OTR specification as compared with a conventional bag design. However the stand-up feature also requires stiffer polymers. Since polymer OTR decreases as polymer stiffness increases the polymers of choice do not have a high enough transmission rate for most fresh-cut applications. Therefore the majority of stand-up pouches for fresh-cut fruits and vegetables utilize microperforated film technology.

18.1.2.2 Rigid Packaging

In rigid packaging, a rigid tray or container with a removable lid is utilized instead of a flexible film structure. There are a number of rigid packaging formats commonly used in fresh-cut produce applications. The key distinguishing parameter from a modified atmosphere perspective is the method utilized to close or seal the tray or container. Three of the more common rigid tray formats include clamshell, snap on lid, and sealable, easy-peel lidding film. The first two formats clamshell and snap on lid are not true modified atmosphere applications since package gas transmissions are not engineered or controlled. Frequently these styles of rigid packages are refered to as natural aspiration packages, meaning that the final atmosphere in the package can vary according to how tight the lid is attached or "snapped" onto the tray. The third format, sealable, easy-peel lidding film, is a true MAP application. The lidding film is designed to a specific gas transmission rate and hermetically sealed onto upper lip of the tray. In all current rigid packaging formats, the tray itself is exempt from the package OTR calculations since it has a negligible OTR, often less than 5 cc/100 in.^{2}/mil/atm/day (77 mL/m^2/mil/atm/day). Therefore when calculating the target OTRs of the package the surface area portion of the calculation is limited to the surface area of the lidding. This generally is a small portion of the total tray surface area and hence the lidding film structures need to have a very high OTR. This high OTR requirement dictates that, for most rigid tray lidding applications, microperforation technology is the only acceptable choice. This requirement is often exacerbated by a printed label placed on the lid further reducing the effective surface transmission area. These gas transmission surface area limitations can lead to microenvironments within the tray. Produce that is in close proximity to the high OTR microperforated lid may have close to the targeted modified atmosphere but produce that is located in the lower corners of the very low OTR rigid tray can experience a significantly different modified atmosphere. Anaerobic conditions are not uncommon in this latter location of a rigid tray packaging system especially if the package is designed to have a low O_2 target atmosphere. Microatmospheres within the tray can lead to shortened shelf life and there is currently research underway to design trays which can participate in the overall OTR of such packages.

The sealing properties of lidding films to rigid trays are significantly different than desired flexible packaging properties. Unlike flexible packaging films, which generally seal similar polymers to each other, rigid packaging design have to produce and effect seal between very dissimilar polymers. Rigid trays are commonly made from polymers such as amorphous polyethyleneterapthalate (APET), polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS). Sealing polymers, especially if they are easy-peel, are frequently made from high percentage ethylene vinyl acetate (EVA) and acid-modified vinyl acetates. The sealing parameters required to achieve an effective seal with dissimilar polymers is much narrower than when sealing a like polymer and hence there is a higher risk for improper sealing with such lidding film. Packaging, which has not been properly sealed, is prone to leaks and since the purpose of MAP is to design and control gas diffusion through a package, leaks in the seal area will cause the system to become out of control. When the packaging system is not a controlled process, optimal shelf life is not attainable.

Rigid packaging provides a number of distinct offerings over flexible packaging including; greater physical protection for sensitive produce, provision of a rigid bowl or tray may be used as the serving vessel by the consumer and the rigid packaging can be made stackable allowing for ease of retail display. However, with the last feature caution must be exercised when rigid trays are stacked the effective OTR surface area of the lidding may be significantly decreased.

18.1.2.3 Active and Intelligent Packaging

Packaging engineers and designers have been working on ways to engineer packaging such that MAP takes an even more active role in protecting and maintaining the quality of fresh-cut produce (Ozdemir and Floros, 2004). Common examples of active packaging include antimicrobial packaging, temperature sensitive switches, absorbent packaging, and cook-in packaging.

The concept behind antimicrobial packaging is to have the package actively participate in the safety of the fresh-cut produce by providing a kill step for any pathogenic bacteria that may be present. There have been and continue to be numerous attempts to develop effective antimicrobial packaging. The focus of the research has been to incorporate a biocide into the package that kills the potentially harmful bacteria. There are a number of challenging technical and regulatory hurdles that must be overcome in order to achieve a working solution including identification of effective antimicrobials, which can be in direct contact with food, regulations, and labeling requirements. Additives incorporated or placed within the package will need to meet all applicable FDA direct food contact regulations (Shanklin and Sánchez, 2005), as well as EPA regulations for pesticides or biocides. As the issue of food safety continues to be priority in the fresh-cut industry so will the interest to support research to finding effective and safe antimicrobial packaging film technologies.

Landec Corporation has been the leading source for temperature switch polymers (Landec, 2007): their Intelimer® polymers are unique materials that respond to temperature changes in a controllable, predictable way. These polymers can abruptly change their permeability, adhesion, viscosity or volume when heated or cooled by just a few degrees above or below a preset temperature switch. The changes are triggered by a built-in temperature switch, which can be set within temperature ranges compatible with most biological applications. Moreover, because the process of change involves a physical and not a chemical change, it can be reversed. Temperature switch polymers can be an effective packaging tool to avoid anaerobic conditions as a result of temperature variation and abuse during the product life cycle. However, temperature switch polymers should never be used in lieu of proper temperature control procedures.

Absorbent packaging describes a packages ability to absorb liquids or gases produced by fresh-cut produce (Ozdemir and Floros, 2004; Brody, 2005). Build up of gases such as ethylene, the ripening hormone, can significantly reduce shelf life. Gas absorption technologies include sachets placed inside the package, and additives within the inner polymer layer. Unlike gas transmission technology which allows gases to leave the package entirely, gas absorption technology absorbs and traps it within the package. The net effect of the two technologies can be similar. Additives incorporated or placed within the package will need to meet all applicable FDA direct food contact regulations. Gas absorption technology is applicable to all types of packaging formats.

Liquid absorption or liquid control has grown with the introduction and growth of the fresh-cut fruit market. Liquid absorption technologies work by trapping or venting liquid into another portion of the package and holding it there. Technologies can include absorbent pads, absorbent gels, and valve films, in combination with compartmentalized rigid packaging. Removal of the liquid from the fresh-cut produce can extend shelf life and trap microorganisms as well as preventing recontamination from the liquid. Although most commonly found in combination with rigid packaging this technology can be adapted to flexible packaging.

Cook-in packaging within the fresh-cut market has seen significant growth within the last 5 years (Forney, 2007). Although most leafy greens are not appealing when cooked, spinach being the exception, the fresh-cooked vegetables market is enjoying significant growth. Cook-in packaging for fresh-cut vegetables is designed for microwave cooking, directly utilizing the heat generated by the microwaves and also the resultant steam generated within the package by the heat (Forney, 2007). The packaging is designed to allow steam pressure build up to a predetermined level and then automatically vent.

A variety of steam venting technologies and formats are available to the package designer. In addition to the standard fresh-cut MAP requirements, functional and regulatory applicability must be considered. Not all polymers commonly used on fresh-cut produce packaging can functionally withstand the temperatures created by steam cooking. Temperatures are significantly higher when oil-based sauces are in used combination with the produce. In addition, not all polymers maintain their direct food contact regulatory status at elevated temperatures. Therefore when designing packaging for cook-in applications, a thorough and complete understanding of cooking temperature and duration are vital in determining polymer functional and regulatory compliance. In addition any additives added to the inner polymer layer such as antifog agents need to be both functional and regulatory compliant.

18.1.3 Packaging Misconceptions

MAP can extend the shelf life of fresh-cut produce items but only under specified ranges of environmental parameters and conditions. There are a number of misconceptions regarding what MAP can and cannot do. First and foremost MAP is only effective if there is consistent temperature management throughout the entire life cycle of the product. This includes during processing right through the entire distribution channel. Lack of temperature control will result in produce respiration variations, which will prevent the packaging system from consistently achieving its targeted optimal modified atmosphere. As previously noted, temperature switch polymers can, to an extent, negate this problem.

MAP will never improve the quality of the incoming raw material product. Under ideal circumstances, the best that can be achieved is to maintain the existing quality level throughout the product life cycle, including shelf life at the consumer level. In real-world applications, MAP will maintain quality for the majority of the targeted shelf life, but due to factors such as loss of temperature control, quality will only visibly suffer at the very end of the desired shelf life.

Fresh-cut MAP relies on the relationship between produce respiration and package transmission rate to alter the atmosphere within the package. This process generally takes a number of days to reach the target atmosphere and equilibrium. For produce items which are prone to enzymatic browning reactions or "pinking," which can be exacerbated by O_2 partial pressures above 3 kPa, this gradual descent may be too long to be helpful for quality maintenance. Hence, gas flushing of fresh-cut MAP has been developed as an approach to establish an initial low oxygen atmosphere within the package, which can be beneficial in reducing enzymatic browning reactions and "pinking." However, gas flushing is not a substitute for proper package design or a compensation for packages that leak after sealing. Effects of gas flushing are only realized when it is employed in combination with proper package design and a leak-free package seal. Since the primary goal of gas flushing is to reduce the initial O_2 level within the package N_2 has proven to be the most effective and economical gas to use for this purpose.

18.2 Atmosphere Effects

18.2.1 Physiology

It has been generally established that prolonged shelf-life of fresh-cut produce is achieved through the reduction of respiration rate, decrease in ethylene biosynthesis and action, and a delaying of senescence (Mir and Beaudry, 2004; Varoquaux and Ozdemir, 2005). This

TABLE 18.1
Summary of Modified Atmosphere Recommendation for Fresh-Cut Vegetables

Fresh-Cut Vegetable	Temperature (°C)	Atmosphere (kPa O_2)	Atmosphere (kPa CO_2)	Efficacy
Beets (red), grated, cubed, or peeled	0–5	5	5	Moderate
Broccoli, florets	0–5	2–3	6–7	Good
Cabbage, shredded	0–5	5–7.5	15	Good
Cabbage (Chinese), shredded	0–5	5	5	Moderate
Carrots, shredded, sticks, or sliced	0–5	2–5	15–20	Good
Jicama, sticks	0–5	5	5–10	Good
Leek, sliced	0–5	5	5	Moderate
Lettuce (butterhead), chopped	0–5	1–3	5–10	Moderate
Lettuce (green leaf), chopped	0–5	0.5–3	5–10	Good
Lettuce (iceberg), chopped or shredded	0–5	0.5–3	10–15	Good
Lettuce (red leaf), chopped	0–5	0.5–3	5–10	Good
Lettuce (Romaine), chopped	0–5	0.5–3	5–10	Good
Mushroom, sliced	0–5	3	10	Not recommended
Onion, sliced or diced	0–5	2–5	10–15	Good
Peppers, diced	0–5	3	5–10	Moderate
Potato, sliced or whole peeled	0–5	1–3	6–9	Good
Pumpkin, cubed	0–5	2	15	Moderate
Rutabaga, sliced	0–5	5	5	Moderate
Spinach, cleaned	0–5	0.8–3	8–10	Moderate
Tomato, sliced	0–5	3	3	Moderate
Zucchini, sliced	5	0.25–1	—	Moderate

Source: Reproduced from Gorny, J.R., *Proc. 7th Intl. Controlled Atmosphere Res. Conf.*, 5, 1997, pp. 30–66. With permission.

directly mediated by low O_2 and/or high CO_2 partial pressures (Varoquaux and Ozdemir, 2005). However, there must be caution raised in regards to package overmodification (i.e., anaerobic levels of O_2 and excessive levels of CO_2), which leads to significantly altered respiratory metabolism and results in development of off-odors and off-flavors (Al-Ati and Hotchkiss, 2002; Watada et al., 2005).

The effect of MAP on the physiology of fresh-cut produce is well documented (Toivonen and DeEll, 2002; Mir and Beaudry, 2004; Varoquaux and Ozdemir, 2005). Tables 18.1 and 18.2 list the currently accepted optimal atmospheres and handling temperatures for selected fresh-cut fruits and vegetables. However, caution must be taken in the application of the recommendations for the optimum atmospheres for given commodity since there may be varying responses by a product as a consequence of differences in physiological maturity, growing conditions, postharvest handling conditions prior to cutting and the expected storage/distribution temperature (Toivonen and DeEll, 2002). It is prudent to verify the efficacy and safety of a given recommendation for a specific situation before applying in commercial practice.

Membrane stability, or retention of membrane function, has not been widely discussed in reviews on MAP effects on fresh-cut product. Loss of membrane integrity is often considered a consequence of oxidative injury in the tissues but the underlying cause may be one of numerous stress factors (Hodges and Toivonen, 2007). Luo et al. (2004) have been able to demonstrate that one of the effects of inadequate permeability is the loss of membrane integrity in packaged cilantro leaves. Cilantro leaves packaged in moderate and fast OTR and microperforated film reached atmospheric equilibrium

TABLE 18.2

Summary of MA Recommendation for Fresh-Cut Fruits

Fresh-Cut Fruit	Temperature (°C)	Atmosphere (kPa O_2)	Atmosphere (kPa CO_2)	Efficacy
Apple, sliced	0–5	<1	4–12	Moderate
Cantaloupe, cubed	0–5	3–5	6–15	Good
Grapefruit, sliced	0–5	14–21	7–10	Moderate
Honeydew, cubed	0–5	2	10	Good
Kiwifruit, sliced	0–5	2–4	5–10	Good
Mango cubes	0–5	2–4	10	Good
Orange, sliced	0–5	14–21	7–10	Moderate
Peach, sliced	0	1–2	5–12	Poor
Pear, sliced	0–5	0.5	<10	Poor
Persimmon, sliced	0–5	2	12	Poor
Pomegranate, arils	0–5	—	15–20	Good
Strawberry, sliced	0–5	1–2	5–10	Good
Watermelon, cubes	0–5	3–5	10	Good

Source: Reproduced from Gorny, J.R., *Proc. 7th Intl. Controlled Atmosphere Res. Conf.*, 5, 1997, pp. 30–66. With permission.

ranging from 1.5 to 21 kPa O_2 and 0 to 3.6 kPa of CO_2. The cilantro in these three package types maintained a low tissue electrolyte leakage throughout the 14 days storage at 0°C. However, those held in packages with low OTR developed an overly modified atmosphere of 0.02 kPa O_2 and 9.0 kPa CO_2. The tissue electrolyte leakage for cilantro in the low OTR packages was significantly higher within 6 days storage and continued to increase over the remainder of the 14 days storage. This data suggests that tissue membranes are plastic and can readily adapt to a wide range of atmospheres in MAP. However, the membrane plasticity has a limit and when anaerobic conditions develop, they rapidly lose their function and cell membrane breakdown occurs and consequently quality declines.

The duration of exposure to anaerobic atmospheres can influence the tissue electrolyte leakage also. Kim et al. (2005b) studied the effect of initial oxygen level on the physiological response of fresh-cut romaine lettuce. Increasing the initial headspace O_2 concentration at the time of sealing the bag, delayed O_2 depletion within the packages but the final steady-state atmospheres were similar in all cases (Figure 18.2). This was associated with a reduction in the levels of tissue electrolyte leakage (Figure 18.3) and also reduced levels of anaerobic metabolite accumulation (Kim et al., 2005b). Therefore, initial gas composition can have a strong influence on membrane breakdown, particularly in packages made from low OTR films which result in low oxygen atmospheres.

Further studies by Kim et al. (2005a) have suggested that a delay after cutting and before packaging results in an altered initial package atmosphere composition at equilibrium. The reason for this result is relatively straightforward. It is well known that wound-induced respiration results in a rapid utilization of oxygen in freshly cut produce (Toivonen and DeEll, 2002). Delay in packaging allows the produce to undergo this period of high respiration rate and consequently when it is finally packaged, there is reduced initial oxygen consumption. This results in higher equilibrium O_2 partial pressures in the package and consequently less fermentative volatile production and tissue electrolyte leakage (Luo, 2007a,b). However, on the down side, there is an increased potential for enzymatic browning due to prolonged exposure to the ambient air after cutting and wounding.

In general in industry practice, some fresh-cut vegetables and especially lettuce, a rapid establishment of a low O_2 and/or elevated CO_2 environment (otherwise known as active

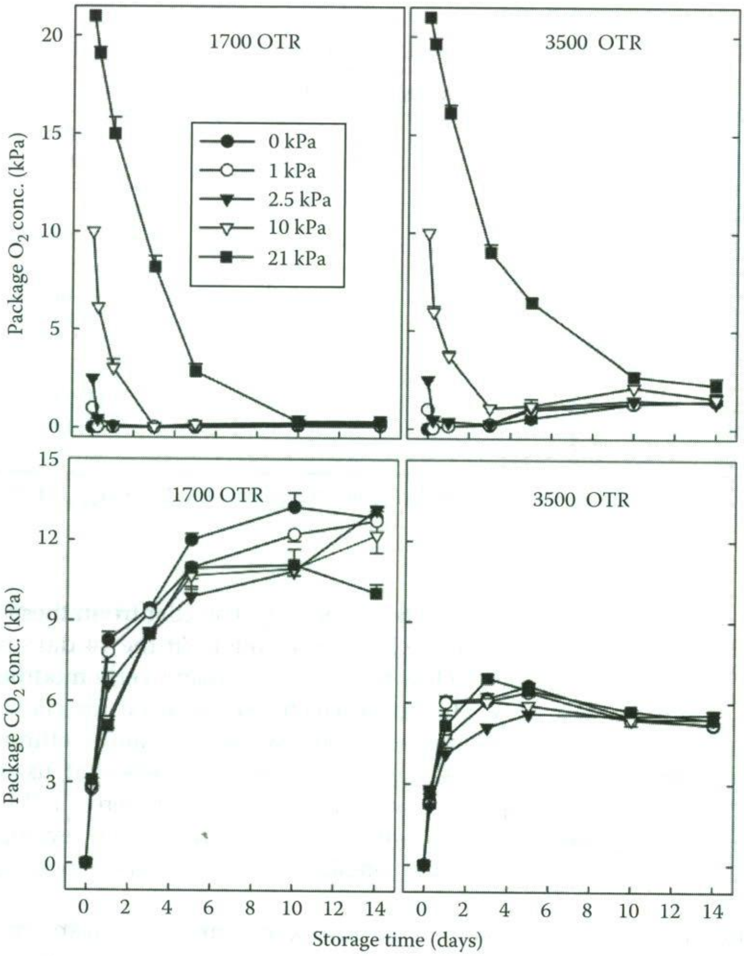

FIGURE 18.2
Effect of packaging film OTR and initial O_2 concentration on aerobic mesophillic bacterial, yeast, and mold populations of packaged fresh-cut romaine lettuce stored at 5°C for 14 days. Packages were flushed with oxygen–nitrogen gas mixtures, sealed in polypropylene film (OTR of 1700 and 3500 mL/days/m^2 at 5°C) packages and stored at 5°C for up to 14 days. Each symbol represents the mean of three replicate measurements and error bars represent standard errors of the mean. (Reproduced from Kim, J., Luo, Y., Saftner, R.A., Tao, Y., and Gross. K.C., *J. Sci. Food Agric.*, 85, 1622, 2005b. With permission.)

MAP) is considered critical for the prevention of cut surface browning (Kim et al., 2005b). This can be attained by flushing the package with N_2, to create an initial low O_2 atmosphere immediately prior to sealing. While gas flushing a package does not alter the equilibrium O_2 and CO_2 concentrations in the headspace, it merely accelerates attainment of the equilibrium concentrations (Kim et al., 2005b). The result of such treatment is not intended to control membrane deterioration, rather to control the activity of polyphenol oxidase, which is largely inactivated at oxygen concentrations below 1 kPa (Smyth et al., 1998). Many researchers have observed that once such packages are opened, they brown extremely rapidly and this suggests that tissue and membrane degradation have occurred, but since oxygen levels were low the interaction between O_2-polyphenol oxidase-phenolic substrates was inhibited until such time as the lettuce was reintroduced to a higher oxygen atmosphere (Smyth et al., 1998).

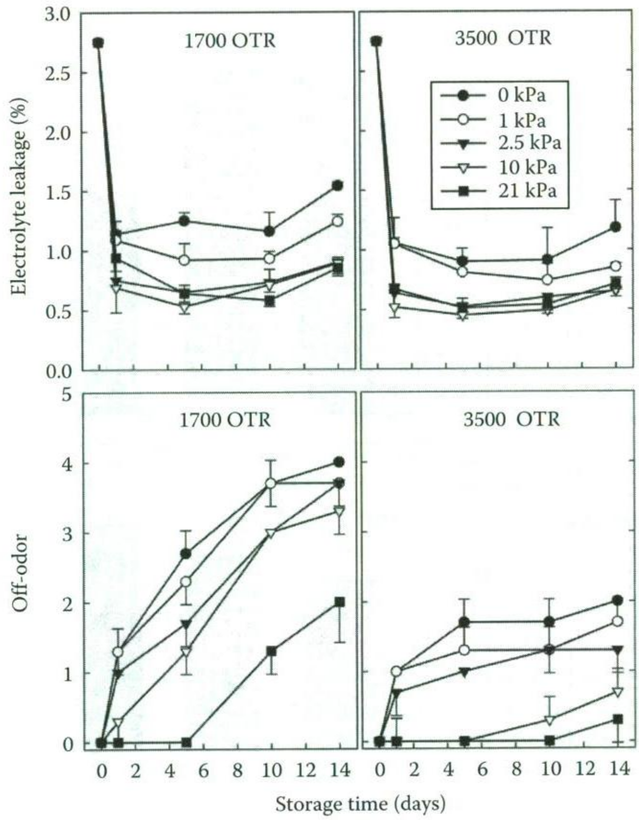

FIGURE 18.3
Effect of packaging film OTR and initial O_2 concentration on electrolyte leakage and off-odor scores of packaged fresh-cut romaine lettuce stored at 5°C for 14 days. Packages were flushed with oxygen–nitrogen gas mixtures, sealed in polypropylene film (OTR of 1700 and 3500 mL/days/m^2 at 5°C) packages and stored at 5°C for up to 14 days. Each symbol represents the mean of three replicate measurements and error bars represent standard errors of the mean. (Reproduced from Kim, J., Luo, Y., Saftner, R.A., Tao, Y., and Gross. K.C., *J. Sci. Food Agric.*, 85, 1622, 2005b. With permission.)

18.2.2 Microbiology

The composition of microbial populations found on commercial fresh-cut products is highly variable. The surface microflora of vegetables and fruits largely comprises *Pseudomonas* spp., *Erwinia herbicola*, *Flavobacterium*, *Xanthomonas*, and *Enterobacter agglomerans*, as well as various yeasts and molds. *Pseudomonas*, particularly *P. fluorescens*, generally dominates the microbial population on many vegetables (Nguyen-The and Prunier, 1989; Babic et al., 1996; Zagory, 1999). Lactic acid bacteria, such as *Lactobacillus* and *Lactococcus*, are also commonly found on fresh-cut fruits and vegetables such as carrots (Zagory, 1999; Allende et al., 2004; Ruiz-Cruz et al., 2006; Luo, 2007a,b). Figure 18.4 shows the typical population counts of aerobic mesospheric bacteria, yeasts, and molds found for various commercially packaged fresh-cut fruits.

The effect of modified atmosphere package conditions on microbial ecology is diverse and is dependent on the microbial species, fresh-cut produce type, and storage conditions (Wang et al., 2004; Watada et al., 2005). The gas composition within packages of fresh-cut produce affects the microbial ecology on the produce. The modified package atmospheres commonly used for fresh-cut produce do not exert biocidal effects on microorganisms,

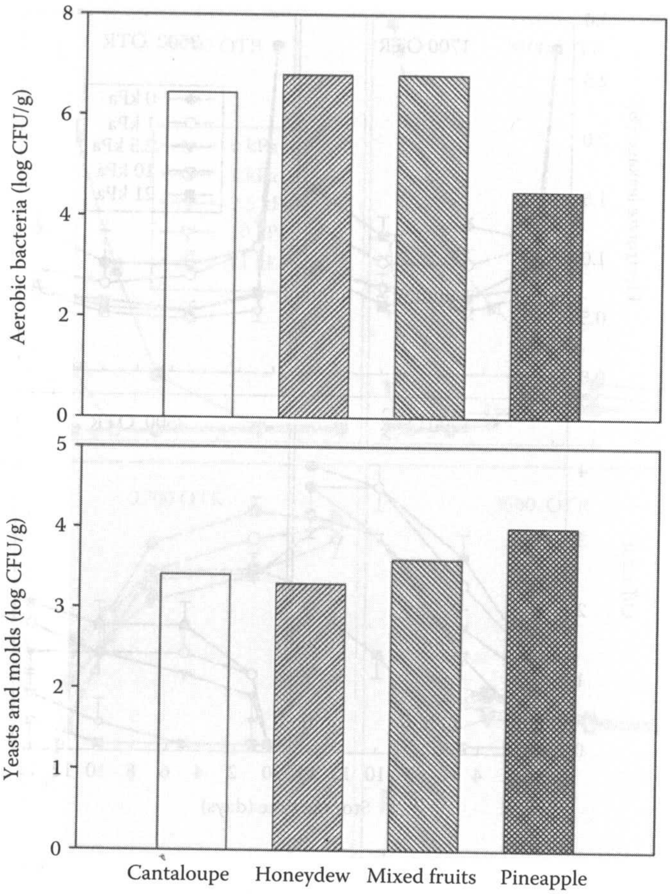

FIGURE 18.4
Aerobic mesophillic bacterial, and yeast and mold populations on various commercially packaged fresh-cut fruits held at 5°C. (Luo, unpublished data.)

but may have a differential influence on the rate of the growth of specific species and therefore the make up of the microbial populations on the packaged products. Elevated CO_2, reduced O_2, or a combination of both can favor the growth of certain classes of microorganisms. For example, a low O_2 plus high CO_2 condition is likely to favor the growth of lactic acid bacteria (Brackett, 1994; Allende et al., 2004).

In general, MAP itself has a limited effect on the growth of aerobic bacteria and any differences in effect may actually be an indirect consequence of the response of the host produce tissue to physiological stress and/or the specific background microbial populations among different fresh-cut products. Luo et al. (2004) examined the microbial growth on packaged fresh-cut cilantro under different atmospheres and reported that there was a gradual increase in aerobic bacterial populations over time regardless of the package atmosphere. Beuchat and Brackett (1990) compared the growth of mesophilic bacteria on shredded lettuce packaged with 3 kPa O_2 and ambient air and found no significant differences between the treatments. Additional studies conducted by Beuchat and Brackett (Brackett, 1994) further concluded that growth of both mesophilic and psychrotrophic aerobic bacteria, yeasts, and molds on sliced tomatoes were essentially unaffected by MAP treatments. In contrast, Babic and Watada (1996) indicated a significant difference of aerobic bacterial growth at different package atmospheres on fresh-cut spinach stored at 5°C in 0.8% O_2 plus 10% CO_2. They reported a 1–2 log reduction in aerobic bacterial populations compared with spinach stored in air at the same temperature. Low O_2, as opposed to high CO_2, seemed to be the limiting factor on the growth of aerobic bacteria on spinach leaves at 5°C, but this relationship did not hold when the spinach was stored at 10°C (Babic and Watada, 1996). *Pseudomonas* sp. counts were lower in a 0 kPa O_2 atmosphere as opposed to a 21 kPa O_2 atmosphere, irrespective of the CO_2 level in the atmosphere. *Pseudomonas* sp. were found to be the predominant spoilage microorganism species in packages in a 21 kPa O_2 atmosphere, whereas *Enterobacter* sp. predominated at a 0 kPa O_2 atmosphere (Babic and Watada, 1996).

On the other hand, growth of anaerobic bacteria can be significantly affected by package atmospheres. Luo et al. (2004) noticed a significant growth in anaerobic bacteria on fresh-cut cilantro leaves packaged in low OTR film when the O_2 was depleted and the CO_2 level was elevated at the end of storage. The effect of MAP on lactic acid bacteria can vary depending on the type of produce packaged. Growth of lactic acid bacteria in response to the elevated CO_2 and decreased O_2 concentrations used in MAP can expedite the spoilage and off-odor development of produce sensitive to lactic acid bacteria, for example lettuce and carrots (Nguyen-The and Carlin, 1994; Ruiz et al., 2006; Luo, 2007a,b).

The growth of yeasts is not generally affected by the package atmosphere composition. However, the extent of yeast growth on different products seems to be extremely variable (Babic et al., 1992, 1996). While high yeast populations were noted in one study on packaged salads toward the end of the MAP storage period (Allende et al., 2006), other researchers have found that yeast populations remain at low levels (10^3–10^4 CFU/g) during an entire storage period in air or controlled atmospheres, at 5°C and 10°C (Babic and Watada, 1996). Fungal growth, on the other hand, can be inhibited by elevated level of CO_2 in the packages (Wells and Uota, 1970) and the population of molds in fresh-cut vegetables is often reported to be very low. The concentration of CO_2 commonly found in packaged salads is usually not considered to be fungicidal.

Atmospheres with O_2 levels higher than 70%, or superatmospheric O_2, have been shown to inhibit microbial growth and enzymatic discoloration and prevent anaerobic fermentation (Day 1996, 2000, 2001). However, the results on packaged vegetable salads are variable (Heimdal et al., 1995; Amanatidou et al., 1999; Day 2001; Allende et al., 2002). Lactic acid bacteria and enterobacteria are inhibited, yeast and *Aeromonas caviae* are stimulated, but psychrotrophic bacteria are unaffected. In general, exposure to high O_2 alone does not have a strong inhibition on microbial growth, while elevated CO_2 generally reduces microbial growth to some extent. The combination of superatmospheric O_2 and elevated CO_2 often exhibits a strong inhibition on microbial growth. As reported by Amanatidou et al. (2000), growth of enterobacteria on fresh-cut carrots was inhibited under 50 kPa O_2 and 30 kPa CO_2, but stimulated under 80 or 90 kPa O_2. With minimally processed vegetables, where CO_2 levels of around 20 kPa or above cannot be used because of physiological damage to the produce, the combined treatment of high O_2 and 10–20 kPa CO_2 may provide significant suppression of microbial growth. However, recent studies by Kader and Ben-Yehoshua (2000) showed that only O_2 atmospheres close to 100 kPa or lower pressures (40 kPa) in combination with CO_2 (15 kPa) are truly effective. These conditions may be difficult to achieve in industry since working with such high O_2 levels can be hazardous due to flammability issues. As with most MAP gases, superatmospheric O_2 has varied effects depending on the commodity, and further research is required in this area to elucidate the utility of this technique in the fresh-cut produce industry.

18.2.3 Quality and Shelf Life

MAP has been shown to increase shelf life of many fresh-cut products (Barriga et al., 1991; Bennik et al., 1996). This phenomenon may or may not be associated with spoilage microorganism growth on the cut surface of the product. Bennik et al. (1996) found that modified atmosphere conditions that were generally favorable for product quality maintenance also retarded growth of spoilage microorganisms at low storage temperatures. However, Barry-Ryan et al. (2000) found that an atmosphere of 3 kPa O_2 and 10 kPa CO_2 maintained acceptable visual quality of lettuce, without appreciably affecting microbial growth (Barriga et al., 1991).

Characteristic quality factors that can shorten shelf life are numerous, including dehydration, discoloration, microbial growth and decay, and off-odor development. While an appropriately developed MAP can assist in increasing shelf life by reducing enzymatic browning, respiration rate, moisture loss, and some microbial growth, it must be accompanied by appropriate storage temperature, minimal physiological damage, and other microbial reduction methods, i.e., produce wash, in order to obtain maximum shelf-life extension. A combination treatment including chlorine prewash, mild heat treatment, MAP, and 5°C storage was able to extend shelf-life significantly for fresh-cut grapes, while none of these processing steps by themselves was able to provide satisfactory quality retention (Kou et al., 2007). There are other examples of the success that can be attained with the use of combined treatment to enhance quality retention (Toivonen and Lu, 2007; Toivonen, 2008) and this trend to combined treatment approaches is likely to increase in the future.

Atmosphere composition may interact synergistically with other protective factors such as storage temperature. While storage of fresh-cut spinach at 5°C in 0.8 kPa O_2 and 10 kPa CO_2 atmospheres reduces aerobic bacterial population by 1–2 log CFU/g as compared with air, bacterial growth increases significantly at 10°C regardless of package atmospheres (Babic et al., 1996).

Although, under conditions that support the physiology of the host plant tissues, some reduction in microbial growth may be attributed to MAP, under conditions of temperature abuse or physiological deterioration the reduction due to MAP is overcome by enhancement of microbial growth on the compromised tissues. As a result of the delicate nature of living plant tissue, extension of shelf-life of fresh-cut produce is best achieved by controlling numerous factors. Shelf-life can be maximized by starting with physiologically healthy, fresh produce; controlling temperature and atmosphere conditions optimally at every stage to minimize microbial growth, dehydration, and senescence. Care must be given to minimize tissue damage during cutting and washing. Packaging film OTR should be selected to meet product respiratory requirements and initial gas mixture should be selected carefully taking into consideration of the unique characteristics of fresh-cut fruits and vegetables.

18.3 Elevated Modified Humidity Effects

While the application of MAP has been targeted to impacting the respiratory metabolism of whole and fresh-cut produce, a side effect (usually considered a side-benefit) has been the maintenance of high humidity around the produce. It has been stated that one of the greatest impacts MAP has in fresh-cut produce is in controlling water loss (Gorny, 1997). Nevertheless, there is only sparse information on the impact of humidity and its control in modified atmosphere package systems. There are some indications that more research in this area may provide new opportunities for MAP technology.

Humidity is generally considered a driving force for water loss, however, it is actually the water vapor deficit (WVPD) between the product and its surrounding atmosphere, which truly defines rate of water loss (van den Berg, 1987). The WVPD is not only affected by relative humidity, but is also influenced by the ambient air temperature and product temperature. The relationship between these factors is clearly shown in the equation which describes the calculation of the WVPD:

$$\text{WVPD} = \text{VP}_{\text{sat-prod}} - (\text{VP}_{\text{sat-air}} \times \text{RH}_{\text{air}}) \tag{18.2}$$

where

$\text{VP}_{\text{sat-prod}}$ is the saturated vapor pressure at the temperature of the fruit or vegetable
$\text{VP}_{\text{sat-air}}$ is the saturated vapor pressure at the temperature of the air surrounding the product
RH_{air} is the relative humidity of the air surrounding the product

Equation 18.2 has several implications in the understanding of the interaction of product with its surrounding humidity in a package. Probably the most important issue relates to the product temperature. Proper postharvest precooling has been the single most cited issue for maintaining quality in fresh fruits and vegetables (Gillies and Toivonen, 1995). One of the reasons for this is exemplified in an experiment where broccoli was properly hydrocooled or not precooled and then placed into the same relative humidity conditions (Gilles and Toivonen, 1995). The result was the broccoli that was not precooled had a much higher calculated WVPD than did properly precooled broccoli. Resultant quality retention was reduced and weight loss was significantly increased by for the broccoli that was not precooled. This same principle holds true for any product that would be placed into a modified atmosphere package. Hence a caveat for using relative humidity to maintain quality is that the product must also be properly temperature managed. Attempts to manipulate humidity in a package will risk failure if good product precooling is not implemented in practice.

Another good example of the importance of temperature control is exemplified by work in packaged broccoli (Tano et al., 2007; Figure 18.5). Temperature fluctuations can significantly increase weight loss in modified atmosphere package produce. Similar increases in moisture loss with temperature fluctuations have been reported previously (Patel and Sastry, 1988; Tano et al., 1999). There are likely a number of factors involved in this increase, including the fact that temperature fluctuations can lead to significant fluctuations in vapor pressure deficit in a fruit or vegetable and potential condensation can occur when temperatures decline during a fluctuation cycle (Patel and Sastry, 1988; Patel et al., 1988; Tano et al., 2007).

Packaging materials can differ in their water transmission properties, and water transmission rates (H_2OTR) do not always parallel gas transmission rates (Table 18.3). A high H_2OTR film would result in a greater flux of water vapor from the package, hence creating a larger WVPD between the fruit or vegetable and the package atmosphere. However, it has been suggested that the humidity in solid film packaging is relatively uniform and hence would not vary largely between packages having large differences in gas transmission rates (Mir and Beaudry, 2004). This is verified by work showing that broccoli weight loss is not significantly different in packages made from films widely varying in both their gas and in H_2OTRs (Table 18.3). Hence, an attempt to control humidity in a solid film package requires the addition of a moisture absorbent.

There have been numerous reports in the literature in regards to modifying moisture in solid film packages using various absorbents, including desiccants, salts, sugar, alcohols, and clay materials (Shirazi and Cameron, 1992; Roy et al., 1995, 1996; Toivonen, 1997a,b; Song et al., 2001; Toivonen et al., 2002; Villaescusa and Gil, 2003; DeEll et al., 2006).

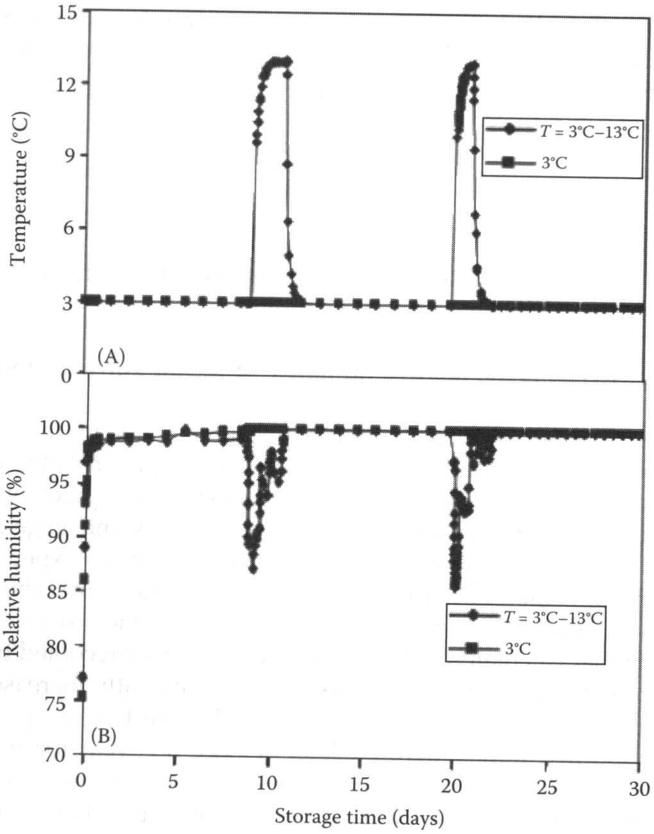

FIGURE 18.5
Changes in temperature (A) and relative humidity (B) levels inside MA packages of broccoli stored at constant temperature: (■) 3°C; under temperature fluctuating conditions: (♦) 3°C–13°C). (Reproduced from Tano, K., Oulé, M.K., Doyon, G., Lencki, R.W., and Arul. J., *Postharvest Biol. Technol.*, 46, 212, 2007. With permission.)

TABLE 18.3

Carbon Dioxide and Water Vapor Transmission Rates (CO_2TR and WVTR, respectively) and Their Ratio for Two Modified Atmosphere Packaging Films and Measured Steady-State CO_2 Levels within Packages Made with These Films Contained Broccoli Heads and the Resultant Weight Loss over 9 Days of Storage at 1°C

Relative Gas Transmission	CO_2TR ($mL/m^2/day$)	Ratio[a] of CO_2TR	Steady-State CO_2 Concentration (kPa)	WVTR ($g/m^2/day$)	Ratio[a] of WVTR	Weight Loss (%)
Fast	71424	2.93	10	13.61	3.67	0.92
Moderate	24389		5	3.71		0.94
Significance	**[b]	**	**	Ns		

Sources: Data extracted from Moyls, A.L., McKenzie, D.-L., Hocking, R.P., Toivonen, P.M.A., Delaquis, P., Girard, B., and Mazza, G., *Trans. ASAE.*, 41, 1441, 1998; DeEll, J.R. and Toivonen, P.M.A., *HortScience*, 35, 256, 2000.

[a] The ratio of transmission rates: the rate for the Fast film divided by the rate for the Moderate film.
[b] Significant at $p < 0.01$.

Another approach to controlling relative humidity inside a package is to modify the film with microperforations. This approach results in a significant modification of the water transmission characteristics of film (Aharoni and Richardson, 1997) and also significant modification of O_2 and CO_2 transmission (Lougheed, 1992). The mode of action of the microperforated film relates to the effect of the microperforations allowing more rapid movement of water vapor into the atmosphere surrounding the package, thereby lowering the internal relative humidity and consequently a slight increase in water loss from product can be measured (Lougheed, 1992).

18.3.1 Physiology

Once a fruit or vegetable is harvested, the main determinants of its water status are the relative humidity surrounding the product and the time since it has been harvested. Washing and hydrocooling steps can "recharge" the product, but that effect is only transient (Shibairo et al., 1998). Therefore a major impact for relative humidity is the determination of water status of the fruit or vegetable tissue. Water status effects on physiology are well studied and so the implications of not maintaining high water status has been discussed in detail elsewhere (Shamaila, 2005).

Water is essential for all metabolic activity in a living cell and hence decline in levels will lead to some form of metabolic impairment or even permanent injury if the level of water loss is great enough (Shamaila, 2005). The level of water loss that leads to significant changes has not been delineated in any of the literature with regard to postharvest handling of fruits and vegetables. It has been demonstrated that peroxidase activity in diced, modified atmosphere packaged onions was sensitive to minor levels of water loss, with a range of approximately 0.2%–0.8% in weight loss coinciding with lowest levels of activity after 9 days storage (Figure 18.6). The initial level of peroxidase in the diced onions at cutting was 1.9 units/mg protein, therefore the peroxidase activity rose significantly over the 9 days in the package, with those packages experiencing moderate water loss showing the lowest levels. These findings suggest that some water loss can be beneficial to modulating wound associated peroxidase activity. Peroxidase activity is important since it is implicated in the development of off-flavors in improperly preserved fruits and vegetables (Burnette, 1977).

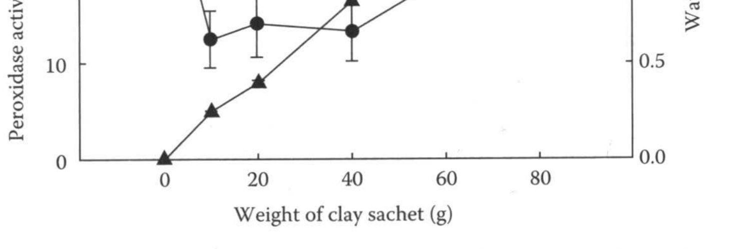

FIGURE 18.6
Changes in peroxidase activity in 'Yellow Colossal' packaged, diced onions associated with differences in water loss within the package due presence of differing weights of sachets containing an adsorbent clay. Data represent means of three replicates and error bars, where not obscured by data points, represent the standard error of those means. A unit of peroxidase activity is defined as a 0.01 unit change in absorbance at 470 nm/min in a mixture containing guaiacol as the substrate. Water loss of the diced onions within a package was inferred by measuring the weight increase of the clay sachet and normalizing this weight against the original total weight of diced onion in a package. (Toivonen, unpublished data.)

TABLE 18.4

Effect of Relative Humidity and Seal-Packaging in High-Density Polyethylene Film on Weight Loss, Firmness, Membrane Integrity, Water Saturation Deficit of Green Bell Pepper Fruit Kept for 4 Weeks at 17°C

Parameter Examined	Treatment			
	WSA[a]	Sealed in HDPE	Nonsealed	Sealed in HDPE + $CaCl_2$ [b]
Weight loss, %	1.76b[c]	1.2a	15.9d	10.5c
Firmness, mm deformation	4.6b	3.3a	12.5d	9.9c
Amino acid leakage, %	14.4ab	11.3a	21.5b	17.3ab
Water saturation deficit, %	11.5a	12.7a	24.4b	20.9b

Source: Data extracted from Ben-Yehoshua, S., Shapiro, B., Chen, Z.E., and Lurie, S., *Plant Physiol.*, 73, 87, 1983. With permission.

[a] WSA refers to a treatment where unpackaged peppers were placed into controlled chamber where relative humidity was maintained at 85% throughout the 4 weeks of holding at 17°C.

[b] Each fruit sealed in a plastic bag containing 5 g of $CaCl_2$ crystals.

[c] Mean separation by Duncan's multiple range test, 1% level.

Ben-Yehoshua et al. (1983) demonstrated that protection against water loss, afforded by plastic film packaging, had a direct effect on the softening process in bell peppers. They found that firmness retention in MA-packaged peppers and those held in a high humidity chamber was significantly better than unpackaged fruit held in normal ambient humidity and those packaged with a desiccant (Table 18.4). The firmness retention in the MA-packaged peppers was partially attributable to better retention of less soluble and insoluble pectin fractions over the 4 weeks storage at 17°C. This retention of less soluble and insoluble pectin fractions was linked to lower levels of polygalacturonase (PG) activity in peppers held in MA compared with those held unpackaged in ambient humidity conditions (Ben-Yehoshua et al., 1983). The direct relationship between water loss and the PG activity was not established, but it may have been associated with the disruption of membrane integrity in the unpackaged peppers as indicated by elevated amino acid leakage values (Table 18.4).

It has been suggested that small amounts of water loss will prevent accumulation of detrimental wound- or ripening-related volatiles (Toivonen, 1997a,b; Toivonen et al., 2002) however, direct proof of this hypothesis is lacking.

18.3.2 Microbiology

Research on the use of humidity control strategies has focused mainly for the control of spoilage microorganisms. It is a well-cited postulate that too high of a humidity leads to condensation within a package and this results in growth of spoilage microorganisms and hence slight lowering of humidity will relieve this problem (Shirazi and Cameron, 1992; Roy et al., 1995; Roy et al., 1996; Fallik et al., 2002; Rodov et al., 2000, 2002; Villaescusa and Gil, 2003). This postulate has been demonstrated to be true in numerous experiments with a large variety of fruits and vegetables, using either absorbents or microperforated films.

Surface browning and/or yellowing and bacterial blotch are symptoms of a *Pseudomonas tolasii* infection in mushrooms and its development is encouraged in sealed modified atmosphere packages that have no humidity control (Roy et al., 1995). Addition of sufficient sorbitol to result in approximately 15% moisture loss at 9 days of 12°C storage provided a significant reduction in discoloration and bacterial surface growth in *Agaricus*

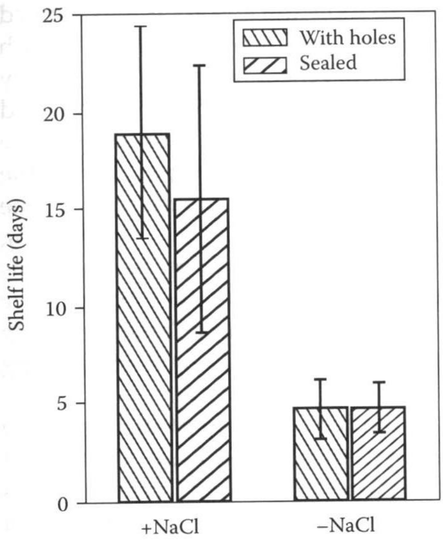

FIGURE 18.7
Effects of controlled humidity on storage life of red-ripe 'Summer Flavor 6000' tomato fruit in modified atmosphere packages. Each bar represents mean shelf life for 18 fruit ± SD. Dry NaCl (10 g/225 g fruit) packed in spun-bonded polyethylene was used to control in-package relative humidity at ~80%. Average O_2 and CO_2 were ~3 kPa and 6 kPa in sealed packages and 17 kPa and 4 kPa in packages with holes. Note: End of shelf life was determined by the growth of *Fusarium* sp. and *Alternaria* sp. on the stem scar of the fruits. (Redrawn from Shirazi, A. and Cameron. A.C., *HortScience*, 27, 336, 1992.)

bisporus mushrooms (Roy et al., 1995). However, if greater amounts of sorbitol were added, greater water loss occurred and quality suffered due to the direct effect of dehydration. The appropriate amount of sorbitol (in regards to controlling bacterial discoloration) resulted in an internal package relative humidity of approximately 85% (Roy et al., 1996).

The fungal decay organisms *Alternaria* sp. and *Fusarium* sp. infecting the stem scar tissue of whole tomatoes can limit shelf life when they are packaged in modified atmosphere packages, which are either solid or microperforated (Shirazi and Cameron, 1992). Application of a desiccant such as sodium chloride will reduce package humidity from near saturation down to approximately 80%, significantly reducing decay-associated loss of shelf life in either solid or microperforated film packages (Figure 18.7). The experience with snap beans has been similar. Fallik et al. (2002) found that maintaining a relative humidity of approximately 90%, using a specialized microperforated film lead to significant reductions in fungal decay of pods when stored at 5°C. In sweet cherries, lowering of relative humidity to approximately 95%, using the same microperforated film, lowered fungal decay incidence from 45% in conventional packages down to 7% after 2 weeks storage at 0°C (Lurie and Aharoni, 1997). Rodov et al. (2002) found that a similar package could essential control rots caused by primarily *Aspergillus* sp. and *Penicillium* sp. in Chanterais-type melons stored at 7°C for 12 days. These results suggest that even moderate reductions in relative humidity can significantly reduce the growth of fungal decay organisms in fruit and vegetable products.

18.3.3 Shelf Life

While the main focus of this chapter is on fresh-cut and modified humidity systems in modified atmosphere packages, there is a significant review on the effects of humidity and water loss existing (Shamaila, 2005). The reader is asked to refer to those reviews for background effects of water loss on quality retention.

The effects on quality and shelf life are the best documented aspect (as opposed to physiological and microbiological aspects) for modified humidity technologies. The most significant effort, on this aspect, has been expended to develop the use of modified humidity systems to preserve the quality of mushrooms (Roy et al., 1995, 1996; Villaescusa and Gil, 2003). That work has focused on the use of various moisture absorbers and applied a varying product to absorber weight ratios. However, it can be difficult to work with such salts. A good example is that provided by the work of Ben-Yehoshua et al. (1983). They applied a treatment where humidity was maintained at approximately 85% in a controlled humidity chamber and a treatment which consisted of a $CaCl_2$ sachet to maintain relative humidity at about 85%. Less than 2% weight loss was experienced by peppers in the controlled humidity treatment, whereas over 10% weight loss was experienced in the sealed packaging containing 5 g $CaCl_2$. Quite clearly, while the $CaCl_2$ was maintaining relative humidity, it was doing it at the expense of the water available from the fruit. This problem is supported by what is known about how saturated salts and other hygroscopic materials maintain relative humidity in experimental systems (Shirazi and Cameron, 1992): if too much adsorbent is used, significant weight loss causing quality loss will occur (Song et al., 2001).

It is clear that the level of water loss experienced is the most important dictate of the resultant quality of fresh-cut products within a humidity-controlled package. There are a few examples which show this principle quite clearly. While much of the data indicates that there is a maximum water loss after which quality declines, there is some data that suggests that no water loss may also be deleterious, especially in regard to flavor change (Figure 18.8). It has been suggested that water loss may enable the removal of wound-induced compounds from tissues, minimizing changes caused by the cutting process in fresh-cut products (Toivonen, 1997a). Hence, in the future when the more subtle issues of flavor change become more important to the fresh-cut industry there may be reason to reexamine the benefits of mild induced water loss and its affect on quality. Meanwhile the greatest impact of humidity control in modified atmosphere-packaged product is the reduction of several postharvest defects including, decay or mold growth in peppers, lemons, and mushrooms (Ben-Yehoshua et al., 1983; Shirazi and Cameron, 1992; Roy et al., 1995, 1996), chilling injury alleviation in mango (Pesis et al., 2000), and prevention of the development of rind disorders in citrus (Porat et al., 2004). The result of humidity control is generally an extended shelf life and quality.

18.4 Challenges Facing the Industry and Future Research Directions

The fresh-cut produce industry faces many challenges, primarily due to the fact that it is a rapidly expanding industry with many new products introduced every year (Brody, 2005; Forney, 2007). As mentioned in the first part of this chapter there is ongoing research into new and improved packaging materials and formats, which may allow the industry to continue to expand, if these new technologies can overcome the inherent limitations of current packaging. New approaches to modifying package atmospheres, such as superatmospheric oxygen combined with high carbon dioxide, may provide new opportunities especially if they can provide a flavor and/or nutritional advantage over existing packaging systems. Certainly greater exploration of combined treatments should be encouraged as the current data clearly show synergistic effects on quality of fresh-cut produce. However, the fundamental shift in research will likely relate to greater focus on flavor, nutritional, and functional quality of fresh-cut products and how they can be better managed with MAP technologies. The reason for this shift is that the category title (i.e., fresh-cut) brings with it an implicit expectation that the product be in a condition which approximates the initial quality at the time of cutting. While at this time visual quality retention is feasible, fresh taste and nutritional and functional qualities of the fresh-cut

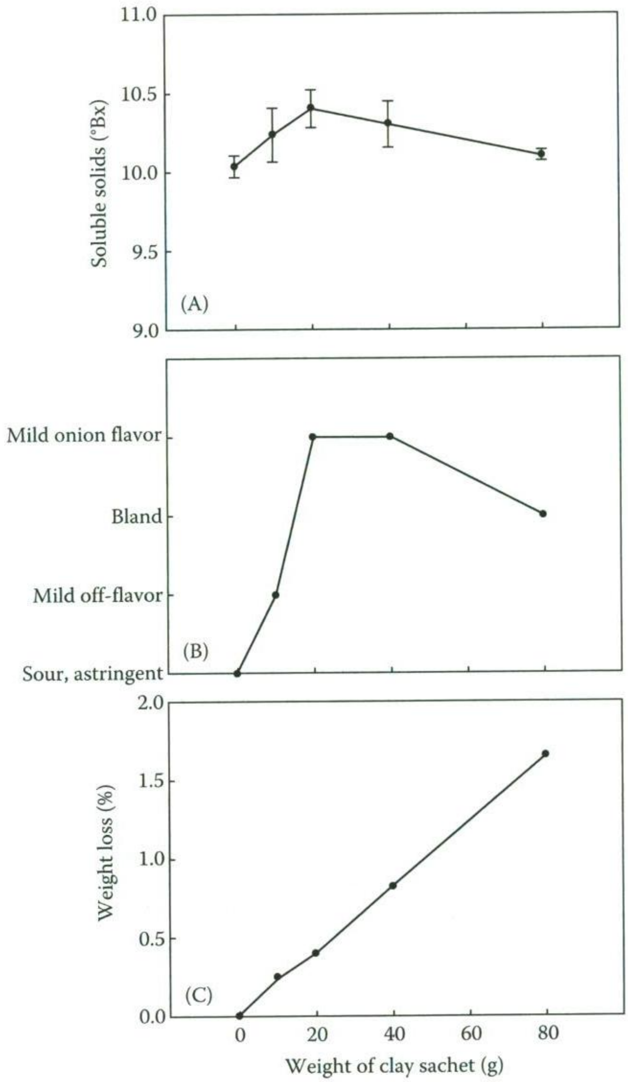

FIGURE 18.8
Effect varying the weight of clay absorbent on soluble solids content (A), flavor (B), and weight loss (C) of modified atmosphere packaged, diced onions (cultivar 'Yellow Colossal') after 9 days of storage at 5°C. Data represent means of three replicates and error bars, where not obscured by data points, represent the standard error of those means. Water loss of the diced onions within a package was inferred by measuring the weight increase of the clay sachet and normalizing this weight against the original total weight of diced onion in a package. (Toivonen, unpublished data.)

product may suffer. There is limited data in regard to the nutritional/functional quality of fresh-cut products suggesting that this does not decline to a large degree over a short shelf life for some products (Gil et al., 2006). However, questions remain as to whether similar results would be obtained under all MAP conditions and under more abusive (realistic) temperature handling conditions. Flavor retention is probably the biggest challenge and perhaps the most important emerging issue for fresh-cut fruit products (Beaulieu and Baldwin, 2002).

References

Aharoni, Y. and D.G. Richardson. 1997. New, higher water permeable films for modified atmosphere packaging of fruits and vegetables. Prolonged MAP storage of sweet corn. *Proc. 7th Int. Controlled Atmosphere Res. Conf.* 4, pp. 73–77.

Al-Ati, T. and J.H. Hotchkiss. 2002. Application of packaging and modified atmosphere to fresh-cut fruits and vegetables, In: O. Lamikanra (Ed.). *Fresh-Cut Fruits and Vegetables: Science, Technology, and Market*. CRC Press, Boca Raton, FL, pp. 305–338 (chap. 10).

Allende, A., L. Jacxsens, F. Devlighere, F. Debevere, and F. Artes. 2002. Effect of superatmospheric oxygen packaging on sensorial quality, spoilage, and *Listeria monocytogenes* and *Aeromonas caviae* growth in fresh processed mixed salads. *J. Food Prot*. 65: 1565–1573.

Allende, A., Y. Luo, J.L. McEvoy, F. Artés, and C.Y. Wang. 2004. Microbial and quality changes in fresh-cut baby spinach stored under MAP and super atmospheric oxygen conditions. *Postharvest Biol. Technol*. 33: 51–59.

Allende, A., J.L. McEvoy, Y. Luo, and C.Y. Wang. 2006. Effectiveness of two-sided UV-C treatments in inhibiting natural microflora and extending the shelf-life of minimally processed 'Red Oak Leaf' lettuce. *J. Food Microbiol*. 23: 241–249.

Amanatidou, A., E.J. Smid, and L.G.M. Gorris. 1999. Effect of elevated oxygen and carbon dioxide on the surface growth of vegetable-associated microorganisms. *J. Appl. Microbiol*. 86: 429–438.

Amanatidou, A., R.A. Slump, L.G.M. Gorris, and E.J. Smid. 2000. High oxygen and high carbon dioxide modified atmospheres for shelf-life extension of minimally processed carrots. *J. Food Sci*. 65: 61–66.

Babic, I., G. Hilbert, C. Nguyen-The, and J. Guiraud. 1992. The yeast flora of stored ready-to-use carrots and their role in spoilage. *Intl. J. Food Sci. Technol*. 27: 473–484.

Babic, I., S. Roy, A.E. Watada, and W.P. Wergin. 1996. Changes in microbial populations on fresh cut spinach. *Intl. J. Food Microbiol*. 31: 107–119.

Babic, I. and A.E. Watada. 1996. Microbial populations of fresh-cut spinach leaves affected by controlled atmospheres. *Postharvest Biol. Technol*. 9: 187–193.

Barriga, M.I., G. Trachy, C. Willemot, and R.E. Simard. 1991. Microbial changes in shredded iceberg lettuce stored under controlled atmospheres. *J. Food Sci*. 56: 1586–1588, 1599.

Barry-Ryan, C., J.M. Pacussi, and D. O'Beirne. 2000. Quality of shredded carrots as affected by packaging film and storage temperature. *J. Food Sci*. 65: 726–730.

Beaulieu, J.C. and E.A. Baldwin. 2002. Flavor and aroma of fresh-cut fruits and vegetables. In: O. Lamikanra (Ed.). *Fresh-Cut Fruits and Vegetables: Science, Technology, and Market*. CRC Press, Boca Raton, FL, pp. 391–425.

Bell, L. 1996. Sealed package containing respiring perishable produce. U.S. Patent # 430,123.

Bennik, M.H.J., H.W. Peppelenbos, C. Nguyen-The, F. Carlin, E.J. Smid, and L.G.M. Gorris. 1996. Microbiology of minimally processed, modified-atmosphere packaged chicory endive. *Postharvest Biol. Technol*. 9: 209–221.

Ben-Yehoshua, S., B. Shapiro, Z.E. Chen, and S. Lurie. 1983. Mode of action of plastic film in extending life of lemon and bell pepper fruits by alleviation of water stress. *Plant Physiol*. 73: 87–93.

Beuchat, L.R. and R.E. Brackett. 1990. Survival and growth of *Listeria monocytogenes* on lettuce as influenced by shredding, chlorine treatment, modified atmosphere packaging and temperature. *J. Food Sci*. 55: 755–758, 870.

Brackett, R.E. 1994. Microbiological spoilage and pathogens in minimally processed refrigerated fruits and vegetables. In: R.C. Wiley (Ed.). *Minimally Processed Refrigerated Fruits and Vegetables*. Chapman & Hall, New York, pp. 269–312.

Brody, A.L. 2005. What's fresh about fresh-cut? *Food Technol*. 56: 124–125.

Burnette, F.S. 1977. Peroxidase and its relationship to food flavor and quality: A review. *J. Food Sci*. 42: 1–6.

Day, B. 1996. High oxygen modified atmosphere packaging for fresh prepared produce. *Postharvest News Inform*. 7: 31–34.

Day, B. 2000. Novel MAP for freshly prepared fruit and vegetable products. *Postharvest News Inform.* 11: 27–31.

Day, B. 2001. *Fresh Prepared Produce: GMP for High Oxygen MAP and Nonsulphite Dipping. Guideline No. 31*, Campden and Chorleywood Food Research Association Group, Chipping Campden, Gloucestershire, U.K., 76 p.

DeEll, J.R. and P.M.A. Toivonen. 2000. Chlorophyll fluorescence as a non-destructive indicator of broccoli quality during storage in modified atmosphere packaging. *HortScience*. 35: 256–259.

DeEll, J.R., P.M.A. Toivonen, F. Cornut, C. Roger, and C. Vigneault. 2006. Addition of sorbitol with $KMnO_4$ improves broccoli quality retention in modified atmosphere packages. *J. Food Qual*. 29: 65–75.

Fallik, E., D. Chalupowicz, Z. Aharon, and N. Aharoni. 2002. Modified atmosphere in a water vapour-permeable film maintains snap bean quality after harvest. *Folia Hort*. 14: 85–94.

Forney, C.F. 2007. New innovations in the packaging of fresh-cut produce. *Acta Hort*. 746: 53–60.

Gil, M.I., E. Aguayo, and A.A. Kader. 2006. Quality changes and nutrient retention in fresh-cut versus whole fruits during storage. *J. Agric. Food. Chem*. 54: 4284–4296.

Gillies, S.L. and P.M.A. Toivonen. 1995. Cooling method influences the postharvest quality of broccoli. *HortScience*. 30: 313–315.

Gorny, J.R. 1997. A summary of CA and MA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables. *Proc. 7th Intl. Controlled Atmosphere Res. Conf.* 5, pp. 30–66.

Heimdal, H., B.F. Kuhn, L. Poll, and L.M. Larsen. 1995. Biochemical changes and sensory quality of shredded and MA-packaged iceberg lettuce. *J. Food Sci*. 60: 1265–1268.

Hodges, D.M. and P.M.A Toivonen. 2007. Quality of fresh-cut fruits and vegetables as affected by exposure to abiotic stress. *Postharvest Biol. Technol*. doi:10.1016/j.postharvbio.2007.10.016

Jacxsens, L., F. Develieghere, and J. Debevere. 2002. Temperature dependence of shelf-life as affected by microbial proliferation and sensory quality of equilibrium modified atmosphere packaged fresh produce. *Postharvest Biol. Technol*. 26: 59–73.

Kader, A.A. and S. Ben-Yehoshua. 2000. Effects of superatmospheric oxygen levels on postharvest physiology and quality of fresh fruits and vegetables. *Postharvest Biol. Technol*. 20: 1–13.

Kim, J., Y. Luo, and K.C. Gross. 2003. Effect of packaging film on the quality of fresh-cut salad savoy. *Postharvest Biol. Technol*. 32: 99–107.

Kim, J., Y. Luo, R.A. Saftner, and K.C. Gross. 2005a. Delayed modified atmosphere packaging of fresh-cut romaine lettuce: Effects on quality maintenance and shelf-life. *J. Am. Soc. Hort. Sci*. 130: 116–123.

Kim, J., Y. Luo, R.A. Saftner, Y. Tao, and K.C. Gross. 2005b. Effect of initial oxygen concentration and film oxygen transmission rate on the quality of fresh-cut romaine lettuce. *J. Sci. Food Agric*. 85: 1622–1630.

Kou, L., Y. Luo, D. Wu, and X. Liu. 2007. Effects of mild heat treatment on microbial populations and product quality of packaged fresh-cut table grapes. *J. Food Sci*. 72: S567–S573.

Landec. 2007. *Technology*. Landec Corporation, Menlo Park, CA. http://www.landec.com/technology.html

Lougheed, E.C. 1992. Microperforated plastic packages for fruits and vegetables. Final Report to the Agricultural Research Institute of Ontario, Project #AG2041—Agriculture and Food Research Fund.

Luo, Y. 2007a. Wash operation affect water quality and packaged fresh-cut romaine lettuce quality and microbial growth. *HortScience*. 42: 1413–1419.

Luo, Y. 2007b. Challenges facing the industry and scientific community in maintaining quality and safety of fresh-cut produce. *Acta Hort*. 746: 131–138.

Luo, Y., J.L. McEvoy, M.R. Wachtel, J.G. Kim, and Y. Huang. 2004. Package film oxygen transmission rate affects postharvest biology and quality of fresh-cut cilantro leaves. *HortScience*. 39(3): 567–570.

Lurie, S. and N. Aharoni. 1997. Modified atmosphere storage of cherries. *Proc. 7th Int. Controlled Atmosphere Res. Conf.* 3, pp. 149–152.

Mir, N. and R.M. Beaudry. 2004. Modified atmosphere packaging. In: K.C. Gross, C.Y. Wang, and M.E. Saltveit (Eds.). *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks,* *USDA Handbook* 66. (accessed on November 6, 2007). http://www.ba.ars.usda.gov/hb66/015map.pdf

Moyls, A.L., D.-L. McKenzie, R.P. Hocking, P.M.A Toivonen, P. Delaquis, B. Girard, and G. Mazza. 1998. Variability in O_2, CO_2 and H_2O transmission rates among commercial polyethylene films for modified atmosphere packaging. *Trans. ASAE*. 41: 1441–1446.

Nguyen-The, C. and F. Carlin. 1994. The microbiology of minimally processed fresh fruits and vegetables. *Crit. Rev. Food Sci. Nutr*. 34: 371–401.

Nguyen-The, C. and J.P. Prunier. 1989. Involvement of pseudomonads in deterioration of "ready-to-use" salads. *Intl. J. Food Sci. Technol*. 24: 47–58.

Ozdemir, M. and J.D. Floros. 2004. Active food packaging technologies. *Crit. Rev. Food Sci. Nutr*. 44: 185–193.

Patel, P.N. and S.K. Sastry. 1988. Effects of temperature fluctuation on transpiration of selected perishables: Mathematical models and experimental studies. *ASHRAE Trans*. 94: 1588–1601.

Patel, P.N., T.K. Pai, and S.K. Sastry. 1988. Effects of temperature, relative humidity and storage time on the transpiration coefficients of selected perishables. *ASHRAE Trans*. 94: 1563–1587.

Pesis, E., D. Aharoni, Z. Aharon, R. Ben-Arie, N. Aharoni, and Y. Fuchs. 2000. Modified atmosphere and modified humidity packaging alleviates chilling injury symptoms in mango fruit. *Postharvest Biol. Technol*. 19: 93–101.

Porat, R., B. Weiss, L. Cohen, A. Daus, and N. Aharoni. 2004. Reduction of postharvest rind disorders in citrus fruits by modified atmosphere packaging. *Postharvest Biol. Technol*. 33: 35–43.

Rodov, V., A. Copel, N. Aharoni, Y. Aharoni, A. Wiseblum, B. Horev, and Y. Vinokur. 2000. Nested modified-atmosphere packaging maintain quality of trimmed sweet corn during cold storage and the shelf life period. *Postharvest Biol. Technol*. 18: 259–266.

Rodov, V., B. Horev, Y. Vinokur, A. Copel, Y. Aharoni, and N. Aharoni. 2002. Modified-atmosphere packaging improves keeping quality of Charentais-type melons. *HortScience*. 37: 950–953.

Roy, S., R.C. Anantheswaran, and R.B. Beelman. 1995. Sorbitol increases shelf life of fresh mushrooms stored in conventional packages. *J. Food Sci*. 60: 1254–1259.

Roy, S., R.C. Anantheswaran, and R.B. Beelman. 1996. Modified atmosphere and modified humidity packaging of fresh mushrooms packaging. *J. Food Sci*. 61: 391–397.

Ruiz-Cruz, S., Y. Luo, R.J. Gonzalez, Y. Tao, and G. Gonzalez. 2006. Effect of acidified sodium chlorite applications on microbial growth and the quality of shredded carrots. *J. Sci. Food Agric*. 86: 1887–1893.

Schlimme D.V. and M.L. Rooney. 1994. Packaging of minimally processed fruits and vegetables. In: R.C. Wiley (Ed.). *Minimally Processed Refrigerated Fruits and Vegetables*. Chapman & Hall, New York, pp. 156–157.

Shamaila, M. 2005. Water and its relation to fresh produce. In: O. Lamikanra, S. Imam, and D. Ukuku (Eds.). *Produce Degradation. Pathways and Prevention*. Taylor & Francis, Boca Raton, FL, pp. 267–291.

Shanklin, A.P. and E.R. Sánchez. 2005. Regulatory Report: FDA's Food Contact Substance Notification Program. October/November 2005, Reprinted from *Food Safety Magazine*. http://www.cfsan.fda.gov/~dms/fcnrpt.html#authors

Shibairo, S.I., M.K. Upadhyaya, and P.M.A. Toivonen. 1998. Replacement of postharvest moisture loss by recharging and its effect on subsequent moisture loss during short-term storage of carrots. *J. Am. Soc. Hort. Sci*. 123: 141–145.

Shirazi, A. and A.C. Cameron. 1992. Controlling relative humidity in modified atmosphere packages of tomato fruit. *HortScience*. 27: 336–339.

Smyth, A., J. Song, and A. Cameron. 1998. Modified atmosphere package of packaged cut iceberg lettuce: Effect of temperature and O_2 partial pressure on respiration and quality. *J. Agric. Food Chem*. 46: 4556–4562.

Song, Y., D.S. Lee, and K.L. Yam. 2001. Predicting relative humidity in modified atmosphere packaging system containing blueberry and moisture absorbent. *J. Food Process. Preserv*. 25: 49–70.

Tano, K., J. Arul, G. Doyon, and F. Castaigne. 1999. Atmospheric composition and quality of fresh mushrooms in modified atmosphere packages as affected by storage temperature abuse. *J. Food Sci.* 64: 1073–1077.

Tano, K., M.K. Oulé, G. Doyon, R.W. Lencki, and J. Arul. 2007. Comparative evaluation of the effect of storage temperature fluctuation on modified atmosphere packages of selected fruit and vegetables. *Postharvest Biol. Technol.* 46: 212–221.

Toivonen, P.M.A. 1997a. Non-ethylene, non-respiratory volatiles in harvested fruits and vegetables: Their occurrence, biological activity and control. *Postharvest Biol. Technol.* 12: 109–125.

Toivonen, P.M.A. 1997b. Quality changes in packaged, diced onions (*Allium cepa* L.) containing two different absorbent materials. *Proc. 7th Int. Controlled Atmosphere Res. Conf.* 5, pp. 1–6.

Toivonen, P.M.A. 2008. Application of 1-MCP in fresh-cut/minimal processing systems. *HortScience*. 43: 102–105.

Toivonen, P.M.A. and J.R. DeEll. 2002. Physiology of fresh-cut fruits and vegetables. In: O. Lamikanra (Ed.). *Fresh-Cut Fruits and Vegetables: Science, Technology, and Market*. CRC Press, Boca Raton, FL, pp. 91–123.

Toivonen, P.M.A., C. Kempler, and S. Stan. 2002. The use of natural clay adsorbent improves quality retention in three cultivars of raspberries stored in modified atmosphere packages. *J. Food Qual.* 25: 385–393.

Toivonen, P.M.A. and C. Lu. 2007. An integrated technology including 1-MCP to ensure quality retention and control of microbiology in fresh and fresh-cut fruit products at non-ideal storage temperatures. *Acta Hort*. 746: 223–229.

Toivonen, P.M.A. and M. Sweeney. 1998. Differences in chlorophyll loss at 13°C for two broccoli (*Brassica oleracea* L.) cultivars associated with antioxidant enzyme activities. *J. Agric. Food Chem.* 46: 20–24.

van den Berg, L. 1987. Water vapour pressure. In: J. Weichmann (Ed.). *Postharvest Physiology of Vegetables*, Marcel Dekker, Inc., New York, pp. 203–230.

Varoquaux, P. and I.S. Ozdemir. 2005. Packaging and produce degradation, In: O. Lamikanra, S. Imam, and D. Ukuku (Eds.). *Produce Degradation: Pathways and Prevention*. Taylor & Francis Group, Boca Raton, FL, pp. 117–153 (chap. 5).

Villaescusa, R. and M.I. Gil. 2003. Quality improvement of *Pleurotus* mushrooms by modified atmosphere packaging and moisture absorbers. *Postharvest Biol. Technol.* 28: 169–179.

Wang, H., H. Feng, and Y. Luo. 2004. Microbial reduction and storage quality of fresh-cut cilantro washed with acidic electrolyzed water and aqueous ozone. *Food Res. Int.* 37: 949–956.

Watada, A.E., H. Izumi, Y. Luo, and V. Rodov. 2005. Fresh-cut produce, In: S. Ben-Yehoshua (Ed.). *Environmentally Friendly Technologies for Agricultural Produce Quality*. CRC Press, Boca Raton, FL, pp. 149–203 (chap. 7).

Wells, J.M. and M. Uota. 1970. Germination and growth of five fungi in low-oxygen and high carbon dioxide atmospheres. *Phytopathology*. 60: 50–53.

Zagory, D. 1998. *An Update on Modified Atmosphere Packaging of Fresh Produce*. Davis Fresh Technologies, Davis, CA. http://www.davisfreshtech.com/articles_map.html (accessed in April 1998).

Zagory, D. 1999. Effects of post-processing handling and packaging on microbial populations. *Postharvest Biol. Technol.* 15: 313–321.